DIOTIC TONAL VOLUMES AS A FUNCTION OF DIFFERENCE OF PHASE[1]

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The fact that a tone, diotically perceived in the presence of a phase-difference between the two ears, is localized toward the side of the leading phase,[2] suggests that the two stimuli, in integrating to form a single tonal sensation, contribute each a tendency to localization toward their respective sides, and that the stimulus leading in phase, because of its priority, contributes to the spatial aspect of the integration more than does the stimulus that lags. When there is no phase-difference localization is in the median plane: both stimuli contribute equally. When one stimulus leads by half a wave-length localization may be entirely to one side: it would seem as if the tone of prior phase were inhibiting the other tone. To such facts the Bernstein theory of localization with the modifications suggested by Boring[3] seems applicable.[4] On the modified Bernstein hypothesis we should expect median localizations, where displaced excitations unite in a single larger region of excitation, to show a large tonal volume (provided, of course, that it should prove to be correct to equate tonal volume to the analogous attribute of spatial diffusion for the skin); and we should expect lateral localizations, where one stimulus inhibiting the other is singly effective, to show a small volume. The present experiment was undertaken in order to test this hypothesis. The results do not substantiate the hypothesis in any simple manner, since the medianly and laterally localized tones are largest and the intermediate tones smallest. The results are, however, positive and univocal, and are presented here without attempt at a theoretical explanation, but with the conviction that an ultimate theory of auditory localization will have to take account of them.

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[1]From the Psychological Laboratory of Clark University.

[2]For the writer's recent papers on this topic and references to the literature, see H. M. Halverson, *Psychol. Monog.*, 1922, no. 140, 7-29; this JOURNAL, 1922, 33, 178-212.

[3]E. G. Boring, *Quart. J. Exp. Physiol.*, 1916, 10, 86-94.

[4]Watt also makes use of the Bernstein theory in his theory of hearing, but in a different manner; H. J. Watt, *Psychology of Sound*, 1917, 175-192; *Brit. J. Psychol.*, 1920, 11, 163-171.

The apparatus was the same as the apparatus for localization with closed tubes described in a previous paper.[5] The source of tone is a 512 d. v. tuning fork, electrically driven by a master-fork. The tone is conducted to the two ears by a pair of rubber tubes which pass through a wall. The phase-relation of the tones of the two tubes is altered by means of a telescopic slide in one of the tubes, which lengthens or shortens the path.

The observers were Mr. M. A. Tinker (*T*), Mr. M. K. Macdonald (*M*), and Mr. F. L. Bixby (*B*), all members of the Psychological Laboratory of Clark University. *T* and *M* were graduate students and trained observers; *B* was a senior of considerable laboratory experience. None of the *O*s, however, had had any previous experience in experimental auditory localization. Their inexperience in localization was considered an advantage in this problem, since the attention was to be to the volumic aspects of the experience and away from its localization.

In order to train the *O*s in volumic judgments and to make sure that their definition of volume had the accepted meaning, a preliminary experiment, patterned after that of Rich[6], was instituted. The *O*s were required to make volumic judgments under the method of constant stimuli upon tones from two Stern variators. The standard was 396 d. v., and the five comparison stimuli ranged from $\frac{1}{8}$ to $\frac{5}{8}$ of a musical tone lower than the standard. At first the *O*s failed to judge consistently. By the end of the second hour, however, *T* and *B* were giving constant results, and by the end of the fourth hour *M* was equally constant. The judgments were not immediate at first, but became immediate as soon as the *O*s had been required to characterize "volume" in a written introspective report. The psychophysical results agree very closely indeed with those of Rich. The average limen for these three *O*s at 396 d. v. is 14.3 d. v. The average limen for Rich's two *O*s at 400 d. v. is 13.4 d. v. Rich's lower limens obtained with tuning-forks[7] are not comparable, since these experiments, like Rich's earlier trials, were with the Stern bottles. The general agreement of these results with Rich's may, however, be taken as an assurance that the *O*s had learned to make judgments of volume as ordinarily defined.

With the *O*s trained to appreciate volumic differences, it was possible to proceed to a preliminary investigation of the volumic relationships of diotic tones where the phase-relationship is varied. Table I gives the results of this preliminary

[5]Halverson, this JOURNAL, 33, 180f.

[6]G. J. Rich, *J. Exp. Psychol.*, 1916, 1, 13-22.

[7]Rich, this JOURNAL, 1919, 30, 149-153.

TABLE I

Preliminary comparison of volumes of diotic tones (512 d. v.; wave-length = 67.3 cm.) for phase-differences of 11.5 cm. (localized 30° left), 24.8 cm. (60° left), and 35 cm. (90° left), compared with zero phase-difference (median localization) as the standard. Observers *T*, *M*, and *B*. Figures are percentages based on 50 judgments for each comparison stimulus.

Localization	30° left			60° left			90° left		
Phase-difference	11.5 cm.			24.8 cm.			35.0 cm.		
Observer	Larger	Equal	Smaller	Larger	Equal	Smaller	Larger	Equal	Smaller
T	0	14	86	0	24	76	16	64	20
M	8	30	62	0	38	62	30	52	18
B	0	32	68	16	34	50	26	56	18
Average	3	25	72	5	32	63	24	57	19

survey. The three phase-differences which give on the average 30°, 60° and 90° left localization were selected for comparison with zero phase-difference, which gives median localization. The table shows that the difference in volume between each of these three comparison stimuli and the standard is not so great as to give univocal judgments. In all three cases the two tones are frequently called "equal," and there are some judgments in the category of difference opposed to the predominant category. Subsequent results (Table II) show, however, that after practice this degree of scatter is reduced. In general it is apparent from Table I that the tone localized at 30° left is predominantly smaller than the medianly localized tone, and that the tone for 60° left is also predominantly smaller, although perhaps not quite so small. For the tone localized laterally at the left, the "equal" judgments predominate; the judgments of "larger" outnumber the judgments of "smaller" for two *O*s, whereas for one *O* the balance is the other way. The lateral tone would thus seem to be of a volume about equal to the volume of the median tone.

The next step is to determine the exact course of the volumic changes, indicated in the preliminary experiment, as phase-difference is altered from zero to the maximum of about a half wave-length, the difference where the tone is localized at 90° left and is about to shift abruptly to 90° right; for a tone leading in phase by more than one-half wave-length is functionally to be regarded as a tone lagging by less than a half wave-length.

The method of procedure was to select zero phase-difference as a standard, and then to determine by the method of constant stimuli the limen for the category "smaller." The

TABLE II

Psychometric functions of volumic differences for phase-differences of diotically perceived tones of 512 d.v. Relative frequencies based on 50 judgments for each comparison stimulus.

Series & standard stimulus (cm.)	Obs.	Range of 5 equally separated comparison stimuli (cm.)	Relative frequencies of volumic difference. I, II, III, "smaller;" IV, V, VI, "larger." Successive comparison stimuli in increasing order of phase-difference: 1	2	3	4	5	Limen by linear inter-polation (cm.)	Average limen (cm.)
I	*T*	6.0–9.0	20	32	52	60	80	7.4	
0.0	*M*	4.0–10.0	20	40	60	74	88	6.3	7.0
	B	5.0–8.0	22	36	44	50	72	7.2	
II	*T*	8.0–12.0	16	38	52	56	68	9.8	
7.0	*M*	8.0–10.0	24	40	66	60	78	8.7	9.2
	B	8.0–10.0	24	24	44	60	78	9.2	
III	*T*	10.0–12.0	28	34	38	52	40	11.5[1]	
9.2	*M*	10.0–12.0	28	38	52	40	52	11.8[2]	11.6
	B	10.0–12.0	18	32	40	46	62	11.6	
IV	*T*	18.0–30.0	10	30	32	62	74	25.8	
11.6	*M*	16.0–24.0	22	36	40	46	68	22.4	24.5
	B	22.0–27.0	20	26	40	56	66	25.3	
V	*T*	28.0–32.0	22	40	52	66	84	29.8	
24.5	*M*	25.5–31.5	26	38	54	70	94	28.1	29.7
	B	27.0–32.0	14	26	34	42	62	31.2	
VI	*T*	31.0–35.0	20	18	28	44	42	[3]	
29.7	*M*	31.0–35.0	24	36	40	50	54	34.0	
	B	33.0–35.0	18	24	30	32	44	[3]	

[1]Minimum of psychometric function from parabola through points 3, 4, and 5. Limen equivocal.
[2]Minimum of psychometric function from least-square parabola through all five points. Limen equivocal.
[3]Limen indeterminate; psychometric function does not include 50%.

*O*s were allowed to report "smaller," "equal," or "larger," but of course no limen for "larger" could be obtained since variation of the stimulus in either direction from the standard tended to give "smaller." When the first set of limens had been obtained (Series I), the limens were averaged for the three *O*s, and this average was used as a new standard for the determination of a new set of limens (Series II). In this manner it was intended to step off the total volumic range by liminal steps. The limit of volumic increase was, however, reached in the third set of limens (Series III). Here the psychometric functions for the *O*s could not be brought to high relative frequencies of the category "smaller;" the minimum volume had been reached, and the functions were reversing direction. Indeed the psychometric functions only barely crossed the 50% abscissa in the cases of *T* and *M*, and returning across it left the exact value of a limen equivocal. For this reason in the column of limens in Table II minima instead of limens are given for these two *O*s. The minimum for *T* was found by passing a parabola through the last three points, and that for *M* by adjusting a parabola by the method of least squares to the entire five points.

Since Series III brought *E* to the volumic minimum, it was necessary for him in Series IV to proceed with limens for the category "larger," just as he had to work only with the category "smaller" when at the maximum in Series I. Series IV was taken with the average of the two minima and one limen of Series III as a standard. Series V was based on the average limen of Series IV, and Series VI on the average limen of Series V. In Series VI maxima were reached, not in the sense that the function again reversed direction, but because the tone now tended to shift to the other side of the head, sometimes existing on both sides at once. This complication would have made careful judgment impossible; moreover it indicated that the limit of variation had been reached, since the tones of the right quadrant simply followed the law of the left. Since the maxima for *T* and *B* in Series VI lay below 50% it is not possible to compute limens for them.

The limens of Table II are all computed by linear interpolation between the two relative frequencies adjacent to 50%. It is obvious from a study of the psychometric functions of Series III and VI that the *phi-gamma* hypothesis is not applicable in those cases. It is also a question whether it should be applied in Series I and IV, which also are limiting cases. Moreover, it is questionable whether any general hypothesis, in the face of the insufficiency of knowledge of the function concerned, could have much value. An hypothesis seeks to take into account remote points as well as the adjacent ones in the

determination of the limen, but it depends for any general validity upon the comparability of different regions of the abscissa scale. In the present case the change of volume for change of phase is irregular; for stretches of the abscissa it seems to change scarcely at all, and then an abrupt change appears. For this reason the mere selection of equal increments of phase-difference for the comparison stimuli gives no assurance that the stimuli are equal in a psychophysical sense and that the remote points can be used to determine the limen. There is no perfectly valid way out of the difficulty. The observed fact, assuming continuity of function, is that the limen lies between the stimulus values for the two relative frequencies that include 50%. If one seeks to say just where, one may follow the convention of linear interpolation as readily as any more difficult assumption. As a matter of fact, with unusual psychometric functions of this sort, the limen has very little meaning, and attention has to be paid to the form and nature of the entire function.

In Fig. 1 the data of Table II are shown graphically in such a way as to indicate the general form of the volumic function. Against difference of phase are plotted for each *O* the six psychometric functions of the six successive series. The ordinate scale for each psychometric function is so arranged that its zero comes opposite the limen of the preceding psychometric function. The average limen for any series was taken as the standard for the succeeding series, and the zero for the scale may be placed at the frequency that the standard had in the preceding series, on the assumption that the standard in the new series would give 0% difference with itself (a rough but not perfect assumption, since a time-error may exist). In this manner it is possible to plot off the volumic function with liminal steps as the ordinate unit and roughly to fill in the breaks between the six observed liminal points by plotting the psychometric functions for these points. The total constellation of the grouped psychometric functions of Fig. 1 gives as closely as possible on the basis of these results the form and amount of the volumic function in general.

Inspection of the three charts of Fig. 1 shows striking agreement among *O*s. It is possible to state the form of the function in general for all *O*s.

As phase-difference increases from zero, the decrease in volume of the diotic tone is at first gradual; and then from about $\pi/8$ to $3\pi/8$ there is an abrupt and rapid decrease to the minimum volume, which is about three liminal steps smaller than the volume for the tones in phase. After $3\pi/8$ there appears to be a gradual increase up to a phase-difference of about $3\pi/4$; thereafter the increase in volume is rapid although not

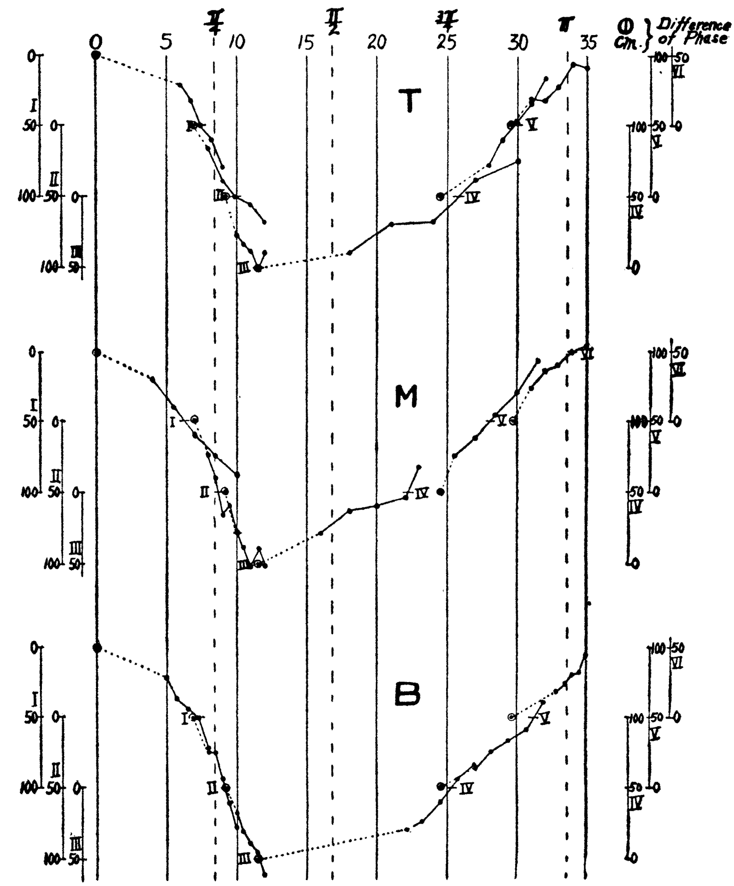

Fig. 1. Volume of diotically perceived tones as a function of difference of phase. Observers *T*, *M*, and *B*. Tones of 512 d. v.; wave-length = 67.3 cm. Abscissa is phase-difference of tones between the two ears, in cm. and wave-length. The psychometric functions for smaller volumes (Series I, II, and III), and for larger volumes (Series IV, V, and VI) are shown successively so scaled that 0% for one function corresponds to the limen of the preceding function, for the reason that the average limen of one function was always used as the standard for the next. For this reason the dotted lines are added on the rough assumption that the standard would give 0% difference from itself as comparison stimulus. The total constellation of the psychometric functions for each *O* gives approximately the form of the function that volume, measured by liminal units (ordinates), is of phase-difference (abscissa).

so rapid as the preceding decrease. The volume reaches a maximum at π where it about equals the volume for zero difference of phase. This last result of Fig. 1 accords with the preliminary results of Table I, which also indicated that the median and laterally localized tones are of about the same volume.

Some *O*s in the localization of diotic tones have described the image of localization as getting farther away from the head when it passes from the median position of localization, and then coming in close to the head when the position of lateral localization is being reached. This change of distance in the image accords with the volumic function; the smaller volumes, it would seem, are perceived as further distant.

The question still remains whether these volumic functions truly represent a distinct volumic aspect of the tonal sensation. There are two other obvious possibilities; the judgments might be dependent entirely or in part upon pitch-difference or upon intensive differences.

The most direct source of information is the *O*s' reports. They consistently described the tones as spatial and their judgments as indicating the spatial aspect. For them the tones are "full," "fat," "lean," "tridimensional," "large," "small," "homogeneously filled," "big," "thin," "extensive," "crowding in from all sides."

The well known association of volumic change with change of pitch and the fact that these *O*s were trained to observe change of volume with change of pitch in the practice-series may nevertheless raise the question whether pitch-differences could be present here and lie at the basis of the volumic function. It is difficult, however, to see how an effective difference of pitch could occur. The lengthening of the one tube with respect to the other might lower the pitch at one side. In such a case there should be binaural beats, but no beats were heard. Moreover a continuous increase of friction would not account for the reversal of the change in the volumic function. It seemed important, nevertheless, to test the matter directly, and the *O*s were asked to make discriminations of pitch between the diotic tone of zero phase-difference and the tone reported as of smallest volume. Both *T* and *M* were unable to detect difference of pitch in a series of over 25 paired presentations. Their results were supported by Dr. Pratt, who has a small limen for pitch discrimination. *B* tended to report differences of pitch; but his capacity for pitch discrimination is known on the basis of tests to be low. With this pair of tones he reported the smaller as higher 9 times, the larger as higher 11 times, and the two as equal 9 times. There is therefore no evidence of a discriminable difference in pitch between the two tones which

give the maximal volumic difference. Similar negative results were obtained from comparing the smallest tone with the lateral tone, and also from comparing the median tone and the lateral tone.

There remains the matter of the relation of volume to intensity. There is no doubt that the diotic tones varied intensively, and casual observation makes it appear as if the intensive function might be similar in form to the volumic. All *O*s mentioned the presence of intensive differences in their protocols. Occasionally they thought that their judgments might have been influenced by intensive differences, but at other times they were positive that they had not been so influenced. For them to have been on their guard against intensity as the basis of judgment gives more assurance that it was not the basis than if they had not mentioned it. On the other hand, it is doubtful whether under these conditions intensity can be separated from volume as was pitch. It is not impossible that the two are essentially covariant. The Bernstein hypothesis, which was responsible for the undertaking of this problem, would imply such a relationship, and, although these experiments have not brought out the function that a modified Bernstein theory implied, they do not disprove the relationship between extensity and intensity that is the basis of that theory. It may be that experiments would show that volume varies with the intensity of a tone in diotic hearing without phase-difference.

Conclusion

Diotically perceived tones vary in their volumic aspect when the phase relationship between them is altered. Medianly localized tones, where the phase-difference is zero, and laterally localized tones, where the phase-difference is half the wave-length, are largest. The intermediate phase-differences give smaller tones, and the minimal volume occurs for a difference in phase of about 3/16 wave-length. These volumic changes are of the same kind as the changes of volume that accompany changes of pitch. They are unaccompanied by changes of pitch under these conditions, but are accompanied by changes of intensity.